MEASURED ENERGY USE INDICES FOR 27 OFFICE BUILDINGS

Jeff Haberl, Atch Sreshthaputra, David Claridge, Dan Turner
Energy Systems Laboratory,
Texas A&M University, College Station, Texas

Kermit Harmon, Julianne Kisselburgh, Rick Mase
Federal Reserve Bank, Dallas, Texas

ABSTRACT

Energy use indices for 27 government office buildings are presented that have been assembled from hourly monitored data as part of the Texas LoanSTAR program and other efforts at the Energy Systems Laboratory. These indices include whole-building electricity, cooling and heating use, as well as the electricity used by the motor controls centers (i.e., fans, pumps, etc.) and the combined lights and receptacles. In this paper a comparative summary of the information is presented across all the sites, as well as tabular information about the indices. Such indices are useful for ascertaining baseline line measurements, or other indicators of energy use in commercial office buildings.

INTRODUCTION

Energy Use Indices (EUIs) have long been a cornerstone for good energy programs in the United States because they provide a reference point, which can be used to compare energy use for building being studied. Most EUIs consists of simple figures-of-merit that normalize energy use for one or more influencing parameters. One of the most common EUIs is to express energy use per square foot of conditioned area, such as annual total consumption expressed as Btu/ft2 or kWh/ft2, or an average power level, expressed as Btu/ft2-hr or W/ft2. Such indices have been used as the basis for government policy in setting energy use reduction goals, or sometimes for comparing the energy use of one building against another.

In general, these indices are calculated by summing 12 utility bills and dividing by the gross conditioned area (CBECS 1997). Occasionally, the information provided by the utility bills is disaggregated into end uses such as heating, cooling and weather-independent use using statistical methods such as PRISM (Fels 1986; Fels et al. 1995), change-point models such as EMODEL (Kissock 1993; Kissock et al. 1994), methods using simulation (Akbari et al. 1988), and hybrid regression methods for public schools (Landman 1998; Landman and Haberl 1998; Noren and Pyrko 1998). In some cases, extensive end-use characterizations have been published for commercial buildings in specific areas of the United States, such as the ELCAP study in the Pacific Northwest (ELCAP 1989), and the buildings that participated in the Energy Edge program, also in the Pacific Northwest (Diamond et al. 1992).

Unfortunately, most of the published annual EUIs for multiple regions can be misleading when the total energy use includes heating, cooling and weather-independent energy use because commercial buildings in different climate regions can have vastly different energy use requirements. For example, office buildings in the hot and humid south have significant year-around cooling requirements. Conversely, buildings in the northern states may have significantly more heating than buildings in the south. This can cause problems for agencies like the Federal Reserve Bank, when it comes time to develop equitable energy management programs that attempt to compare energy use indices for banks in different climate regions.

Therefore, it was decided to comb the database at the Energy System Laboratory to see if it contained a suitable number of office buildings in different locations where hourly energy use had been recorded for various end-uses, including: motor control center (MCC) electricity use , heating, cooling, and weather-independent energy use (i.e., the electricity used by lighting and receptacles). A search of the database at the ESL that contains data on over 400+ buildings determined that 27 office buildings were available that could be used to develop EUIs for heating, cooling, MCC electricity use, and weather-independent electricity use.

This paper presents the results of a study that analyzed information in the database at the Energy Systems Laboratory. The purpose of this analysis was to determine whether or not the hourly data that had been collected for purposes of measuring energy savings could provide useful annual indices about heating, cooling and weather-independent electricity use. To accomplish this a number of procedures had to be developed for baselining the data and then projecting the baseline over an annual period so that EUI could be developed.

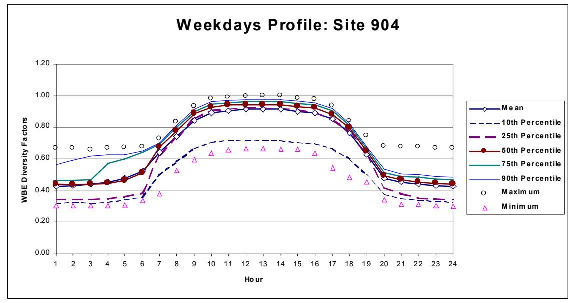
METHODOLOGY

The methodology used to develop EUIs uses analysis techniques that had been shown to be effective for baselining energy use in commercial buildings, including: linear and change-point linear models (Kissock 1993; Kissock et al. 1994), and weekday-weekend diversity factors to derive the electricity EUIs and provide the typical load shapes of lighting and receptacle loads for office buildings, based on an analysis developed for ASHRAE research project 1093-RP that uses a quartile analysis (Abushakra et al. 1999; Abushakra et al. 2000). The 1093-RP daytyping procedure calculates 10th, 25th, 50th, 75th, and 90th percentiles for each hour of the day by daytype (i.e., weekday,weekend). The percentile analysis was chosen because the lighting and receptacle loads represented by the office buildings studied for this project tend to exhibited multi-modal distributions (where the frequency curve exhibits more than two maxima) rather than a normal distribution required by the mean and standard deviation analysis. Furthermore, many of the office buildings had significant outliers that also influence the standard deviation.

Diversity Factors and Load Shapes for Electricity Use

In the calculations of the diversity factors in 1093-RP the 50th percentile values for each hour of the day are the diversity factors values of the lighting and receptacles loads to be used for the energy calculations of office buildings, whereas the 90th percentile values are the values that are recommended for use for peak cooling load calculations. The 50th percentile is the median, which divides the dataset (for most sites this is one year of hourly data) into two equal parts.

The 90th percentile values are recommended for predicting peak cooling loads from light and receptacle loads. An examination of the datasets revealed that the 90th percentile profile is a more realistic value of a peak profile, since the maximum profile is a profile derived from hourly maximums and rarely represents the events of a single day. In some buildings the maximum profile is almost in agreement with the 90th percentile profile, but in few cases there is a considerable difference between those two profiles. Therefore, the typical load shapes produced include not only the 50th and the 90th percentiles, but also the 10th, 25th, and the 75th percentiles, to show the whole band that bounds the data, together with the maximum, minimum, mean, for a better illustration of the variation in the data as shown in Figure 1.



**The dates that are excluded from the weekday profile are as follow: 1/17/94, 1/20/94, 2/11/94, 2/21/94, 5/9/94, 5/30/94, 7/4/94, 9/5/94, 10/10/94, 11/11/94, 11/24/94, 11/25/94, and 12/26/94.*

Figure 1: *Typical Diversity Factor Calculation for Site #904 (weekday) Electricity Data.*

Figure 1 shows the 24-hour weekday profile for Site #904 (U.S.D.O.E. Forrestal Building in Washington, D.C., Bou Saada et al. 1996) that was used to calculate the whole-building electricity profile for this site. In general, the data for each site were inspected for weather-dependent data, which were removed prior to performing the calculation. The annual EUI was then calculated by multiplying the weekday and weekend profiles times 52 weeks (i.e., 5 weekdays and 2 weekend profiles times 52 weeks).

Heating and Cooling EUI Calculations.

The calculations for the heating and cooling EUIs were performed using weekday-weekend daily data for each site (i.e., the hourly data were summed to daily totals before the analysis was performed). Weekday, weekend linear and change-point linear models were then used to represent the weather dependency for each site. For example, in Figure 2 and Table 1 the results of the application of the three parameter model heating model to site #904 (USDOE Forrestal building) are shown.

In Table 1, the model's coefficients are listed along with several statistical parameters, including: Ycp = 32,436.9 kBtu/day, the average daily energy use at the change-point; LS = -10,996.8 kBtu/day-F, the slope of the linear regression line to the left of the change-point; RS = 0.0 kBtu/day-F, the slope of the linear regression line to the right of the change-point

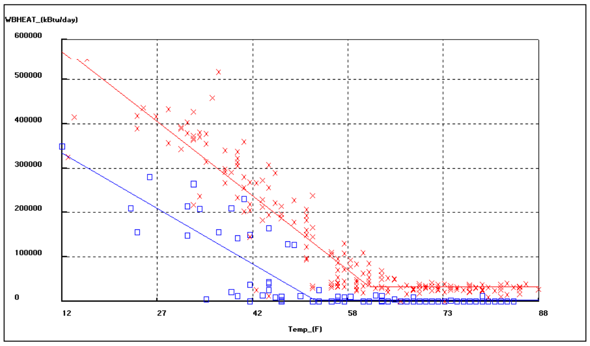


Figure 2: *Typical three Parameter, Weekday-weekend, Change-point Heating Model for Site #904.*

(which is equal to zero for three parameter heating models), Xcp = 61.0 F, the temperature of the change point; N = 185 data points in the regression, N1 = 111 and N2 = 74 are the number of points to the left and right of the change point, respectively, R2 = 0.87 the coefficient of multiple determination, and adjR2 = 0.87 the adjusted coefficient of multiple determination, RMSE = 50,085.95, the root mean square error in kBtu/day, and CV-RMSE = 37.1%, the coefficient of variation of the root mean square error, p = 0.20 is the auto-correlation coefficient of the residual, and DW = 1.53 (p>0) is the Durbin-Watson statistic. Additional explanations of the statistics and the methods used to calculate them can be found in Kissock (1993), and Kissock et al. (1994).

Site # 904, USDOE Forrestal Building, Washington, DC

Whole-Building Heating Energy Use Baseline Model
Period: 1/1/94 to 12/31/94

Model: Multi-group 3P-CP (H). WBHEAT_(kBtu/day) vs. Temp_(F)
Weekday:
Ycp = 32436.8880 (4716.5030) LS = -10996.8220 (315.8825) RS = 0.0000 (0.0000) Xcp = 61.0000
N = 185 N1 = 111 N2 = 74 R2 = 0.87 adjR2 = 0.87 RMSE = 50085.95 CV-RMSE = 37.1% p = 0.20
DW = 1.53 (p>0)
Weekend:
Ycp = 2736.2388 (5315.7240) LS = -8212.1746 (562.1987) RS = 0.0000 (0.0000) Xcp = 52.3200
N = 85 N1 = 31 N2 = 54 R2 = 0.72 adjR2 = 0.72 RMSE = 42545.23 CV-RMSE = 103.1% p = 0.40
DW = 1.15 (p>0)

DATA	MODEL	Ycp	LS	RS	Xcp	AdjR2	CV(RMSE)
WBH - WD	3P	32436.8880	-10996.8220	0.0000	61.0000	0.87	37.1%
WBH - WE	3P	2736.2388	-8212.1746	0.0000	52.3200	0.72	103.1%

Table 1. *Statistics for the Three Parameter, Weekday-weekend, Change-point Model for Site #904*

RESULTS:

Electricity EUI 24-Hour Profiles

To evaluate the electricity use of the 27 buildings, 24-hour profiles were generated using the procedures developed for ASHRAE Research Project 1093RP (Abushakra et al. 1999; 2000). These profiles were calculated from the hourly whole-building electricity data for each site after the weather-dependent usage periods were removed. Each profile contains minimum, 10th, 25th, 50th, 75th, 90th and maximum values for each hour of the day. The 50th percentile was used to calculate the electricity EUIs, and maximum value was used to determine the maximum electric demand (shown in Table 2, column 13, W/ft2). Figure 3 contains the 24-hour profiles for the weekdays, and Figure 4 contains the 24-hour profiles for the weekends. These profiles show the 24-hour weather-independent electricity use as a normalized 0 – 1 index (i.e., whole-building electricity use minus the motor control centers).

In general, these profiles show dramatic differences in their shapes. Most sites show a consistent weekday operation, which can be determined by observing the distance between the 25th and 75th percentiles. In most of the sites unoccupied weekday operation represents about ½ to 2/3 of the occupied period use. Some sites show almost flat weekday 24-hour profiles (e.g., sites 200, 201, 205 and 952), while others show significant night-time shutdown (e.g., sites 963, 951, and 208). Most sites show weekend consumption in the 40 to 60% range. Several sites (i.e., 205, 229, 985, 952) show significant weekend use at 60% of the peak use and above. Two sites show weekend shut down rates at 20% and below.

Annual Electricity, MCC, Cooling, and Heating EUIs.

In Tables 2 and 3 summaries of the Energy Use Indices (EUIs) are presented in several formats. In Tables 2 and 3 the first (13) columns contain similar information. In column 1 the category of the building is listed, where the buildings are categorized by the total building area in ft^2, based on the CBECS classification: Large (L) > 100,000 ft^2, Medium (M) > 10,000 ft^2 and < 100,000 ft^2, and Small (S) < 10,000 ft^2.

In column 2 the number that has been assigned to this site for this report is shown. This also represents the order in which the sites are presented in Section 4. In column 3 the ESL site identification number is shown. This number is used to identify each sites in the graphs and tables that follow. In column 4 a site ID has been assigned to each site that serves to group each site into the respective states: DC, MN, MT, and TX for Washington, D.C., Minnesota, Montana and Texas, followed by S, M, L for small, medium and large classification.

Category	No.	Bldg I.D.	Site ID.	Building	Location	Building Area (sqft)	Start Date	End Date	Daytype Data Type	WBE Data Type	Whole Building EUI: WBE		MCC	WBE-MCC	WBCOOL	WBHEAT
											kWh/ft^2-yr	W/ft^2	kWh/ft^2-yr	kWh/ft^2-yr	$kBtu/ft^2$-yr	$kBtu/ft^2$-yr
L	1	904	DCL001	USDOE Forrestal Building	Washington D.C	1,200,000	1/1/94	12/31/94	WBE	WI	19.64	3.93	-	-	-	31.90
L	2	704	MNL001	State Office Bldg. 1	St. Paul, MN	200,829	1/1/98	12/31/98	WBE	WDH	18.28	4.44	-	-	14.88	22.16
L	3	707	MNL002	State Office Bldg. 2	St. Paul, MN	281,850	1/1/98	12/31/98	WBE	WDH	12.51	2.87	-	-	14.51	18.10
L	4	710	MNL003	State Office Bldg. 3	St. Paul, MN	366,805	1/1/98	12/31/98	WBE	WDH	13.39	2.99	-	-	8.47	22.83
L	5	711	MNL004	State Office Bldg. 4	St. Paul, MN	317,286	1/1/98	12/31/98	WBE	WI	29.24	4.38	-	-	8.26	19.63
M	6	706	MNM001	State Office Bldg. 6	St. Paul, MN	57,047	1/1/98	12/31/98	WBE	WDC+	18.19	3.64	-	-	-	56.20
M	7	709	MNM002	State Office Bldg. 5	St. Paul, MN	87,664	3/1/96	3/1/97	WBE	WDH	11.34	2.78	-	-	15.27	42.61
M	8	712	MNM003	State Office Bldg. 7	St. Paul, MN	77,630	1/1/98	12/31/98	WBE	WDC	22.00	5.36	-	-	5.00	54.19
L	9	963	MTL001	State Office Bldg. 8	Butte, MT	100,000	7/1/98	7/1/99	WBE	WI	4.11	1.13	-	-	-	77.32
L	10	146	TXL001	Government Center	Dallas, TX	473,800	1/1/95	12/31/95	WBE - MCC	WDC+	22.88	4.58	3.53	19.35	87.98	73.45
L	11	203	TXL002	John H. Reagan	Austin, TX	169,746	1/1/97	12/31/97	WBE - MCC	WI	23.63	4.33	2.41	21.22	53.93	32.16
L	12	206	TXL003	Insurance Building [1]	Austin, TX	102,000	1/1/96	12/31/96	WBE - MCC	WI	24.00	4.13	4.89	19.04	145.68	43.03
L	13	208	TXL004	Archives Building [1]	Austin, TX	120,000	1/1/97	12/31/97	WBE - MCC	WI	11.25	2.37	3.81	7.44	68.92	41.94
L	14	209	TXL005	W.B. Travis [2]	Austin, TX	491,000	1/1/97	12/31/97	WBE - MCC	WI	16.53	3.16	0.22	16.31	86.81	49.57
L	15	210	TXL006	L.B. Johnson	Austin, TX	308,080	1/1/97	12/31/97	WBE-MCC-AHU	WI	36.70	5.53	3.05	33.66	140.17	-
L	16	228	TXL007	Price Daniels Building [1]	Austin, TX	151,620	1/1/98	12/31/98	WBE	WI	15.86	2.76	-	-	102.63	38.33
L	17	229	TXL008	Tom C. Clark Building	Austin, TX	121,654	1/1/98	12/31/98	WBE	WI	12.31	1.75	-	-	114.93	28.47
L	18	985	TXL009	Atrium Building	Dallas, TX	100,000	10/1/98	10/1/99	WBE-MCC	WDC+	83.76	13.04	6.69	77.07	8.31	-
L	19	975	TXL010	Brazos County Courthouse	Bryan, TX	100,000	7/1/98	7/1/99	WBE-MCC	WDC+	22.29	4.42	2.48	19.80	23.59	-
L	20	200	TXL011	Capitol Building	Austin, TX	282,499	7/1/97	7/1/98	WBE	WI	21.08	3.39	-	-	130.43	29.15
L	21	201	TXL012	Sam Houston Building [1]	Austin, TX	182,961	1/1/93	12/31/93	WBE	WI	30.13	5.39	-	-	75.86	48.84
L	22	952	TXL013	Records Complex	Dallas, TX	323,232	1/1/98	12/31/98	WBE	WDC+	19.00	6.52	-	-	28.71	-
M	23	205	TXM001	James E. Rudder [1]	Austin, TX	80,000	1/1/94	12/31/94	WBE - MCC	WI	47.53	7.18	-	-	44.92	52.31
M	24	207	TXM002	Insurance Annex [1]	Austin, TX	62,000	1/1/93	12/31/93	WBE-MCC-Chill	WDC+	17.63	3.59	2.46	15.17	12.58	48.83
M	25	226	TXM003	Central Services Building	Austin, TX	97,030	1/1/96	12/31/96	WBE-Chill	WDC+	23.65	4.82	-	-	85.76	-
M	26	227	TXM004	Supreme Court Building [1]	Austin, TX	72,737	1/1/98	12/31/98	WBE	WI	11.60	2.22	-	-	219.08	39.83
M	27	951	TXM005	Administrattion Building	Dallas, TX	42,385	1/1/98	12/31/98	WBE	WDC+	48.17	4.87	-	-	50.11	-

Note:
1. Heating energy is pro-rated from the total heating energy use at the Sam Houston plant that serves this site.
2. Heating energy is pro-rated from the total heating energy use at the S.F. Austin plant that serves this site.

Table 2: Energy Use Indices (EUIs) for 27 Office Buildings (kWh/ft2-yr, W/ft2,Btu/ft2-yr)

									Whole Building EUI						
									WBE		MCC	WBE-MCC	WBCOOL	WBHEAT	TOTAL
Category	No.	Bldg I.D.	Site ID.	Building	Location	Building Area (sqft)	Start Date	End Date	kWh/ft^2-yr	W/ft^2	kWh/ft^2-yr	kWh/ft^2-yr	kWh/ft^2-yr	kWh/ft^2-yr	kWh/ft^2-yr
L	1	904	DCL001	USDOE Forrestal Building	Washington D.C	1,200,000	1/1/94	12/31/94	19.64	3.93	-	-	-	9.35	-
L	2	704	MNL001	State Office Bldg. 1	St. Paul, MN	200,829	1/1/98	12/31/98	18.28	4.44	-	-	1.24	6.50	26.02
L	3	707	MNL002	State Office Bldg. 2	St. Paul, MN	281,850	1/1/98	12/31/98	12.51	2.87	-	-	1.21	5.36	19.08
L	4	710	MNL003	State Office Bldg. 3	St. Paul, MN	366,805	1/1/98	12/31/98	13.39	2.99	-	-	0.71	7.11	21.21
L	5	711	MNL004	State Office Bldg. 4	St. Paul, MN	317,286	1/1/98	12/31/98	29.24	4.38	-	-	0.69	5.76	35.69
M	6	706	MNM001	State Office Bldg. 6	St. Paul, MN	57,047	1/1/98	12/31/98	18.19	3.64	-	-	-	16.47	-
M	7	709	MNM002	State Office Bldg. 5	St. Paul, MN	87,664	3/1/96	3/1/97	11.34	2.78	-	-	1.27	12.51	25.12
M	8	712	MNM003	State Office Bldg. 7	St. Paul, MN	77,630	1/1/98	12/31/98	22.00	5.36	-	-	0.42	15.88	38.30
L	9	963	MTL001	State Office Bldg. 8	Butte, MT	100,000	7/1/98	7/1/99	4.11	1.13	-	-	-	22.66	-
L	10	146	TXL001	Government Center	Dallas, TX	473,800	1/1/95	12/31/95	22.88	4.58	3.53	19.35	7.33	21.53	51.74
L	11	203	TXL002	John H. Reagan	Austin, TX	169,746	1/1/97	12/31/97	23.63	4.33	2.41	21.22	4.49	9.43	37.55
L	12	206	TXL003	Insurance Building [1]	Austin, TX	102,000	1/1/96	12/31/96	24.00	4.13	4.89	19.04	12.14	12.61	48.75
L	13	208	TXL004	Archives Building [1]	Austin, TX	120,000	1/1/97	12/31/97	11.25	2.37	3.81	7.44	5.74	12.29	29.29
L	14	209	TXL005	W.B. Travis [2]	Austin, TX	491,000	1/1/97	12/31/97	16.53	3.16	0.22	16.31	7.23	14.53	38.29
L	15	210	TXL006	L.B. Johnson	Austin, TX	308,080	1/1/97	12/31/97	36.70	5.53	3.05	33.66	11.68	-	-
L	16	228	TXL007	Price Daniels Building [1]	Austin, TX	151,620	1/1/98	12/31/98	15.86	2.76	-	-	8.55	11.23	35.65
L	17	229	TXL008	Tom C. Clark Building	Austin, TX	121,654	1/1/98	12/31/98	12.31	1.75	-	-	9.58	8.34	30.23
L	18	985	TXL009	Atrium Building	Dallas, TX	100,000	10/1/98	10/1/99	83.76	13.04	6.69	77.07	0.69	-	-
L	19	975	TXL010	Brazos County Courthouse	Bryan, TX	100,000	7/1/98	7/1/99	22.29	4.42	2.48	19.80	1.97	-	-
L	20	200	TXL011	Capitol Building	Austin, TX	282,499	7/1/97	7/1/98	21.08	3.39	-	-	10.87	8.54	40.49
L	21	201	TXL012	Sam Houston Building [1]	Austin, TX	182,961	1/1/93	12/31/93	30.13	5.39	-	-	6.32	14.31	50.77
L	22	952	TXL013	Records Complex	Dallas, TX	323,232	1/1/98	12/31/98	19.00	6.52	-	-	2.39	-	-
M	23	205	TXM001	James E. Rudder [1]	Austin, TX	80,000	1/1/94	12/31/94	47.53	7.18	-	-	3.74	15.33	66.60
M	24	207	TXM002	Insurance Annex [1]	Austin, TX	62,000	1/1/93	12/31/93	17.63	3.59	2.46	15.17	1.05	14.31	32.99
M	25	226	TXM003	Central Services Building	Austin, TX	97,030	1/1/96	12/31/96	23.65	4.82	-	-	7.15	-	-
M	26	227	TXM004	Supreme Court Building [1]	Austin, TX	72,737	1/1/98	12/31/98	11.60	2.22	-	-	18.26	11.67	41.53
M	27	951	TXM005	Administrattion Building	Dallas, TX	42,385	1/1/98	12/31/98	48.17	4.87	-	-	4.18	-	-

Note:

1. Heating energy is pro-rated from the total heating energy use at the Sam Houston plant that serves this site.
2. Heating energy is pro-rated from the total heating energy use at the S.F. Austin plant that serves this site.

Table 3: Energy Use Indices (EUIs) for 27 Office Buildings (kWh/ft2-yr, W/ft2)

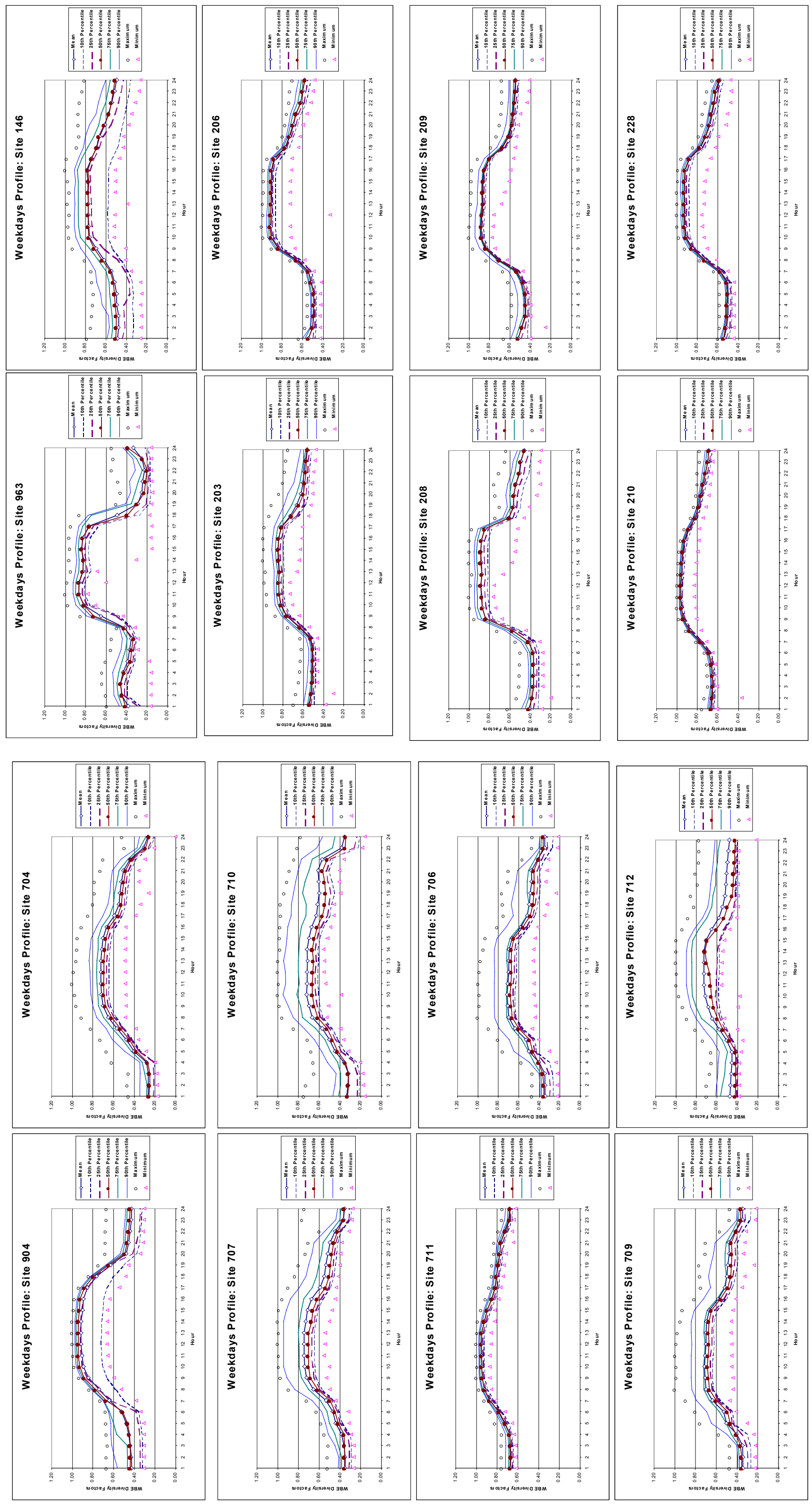


Figure 3: 24-hour, Weekday, Whole-building Electricity Profiles used for EUI Calculations. .

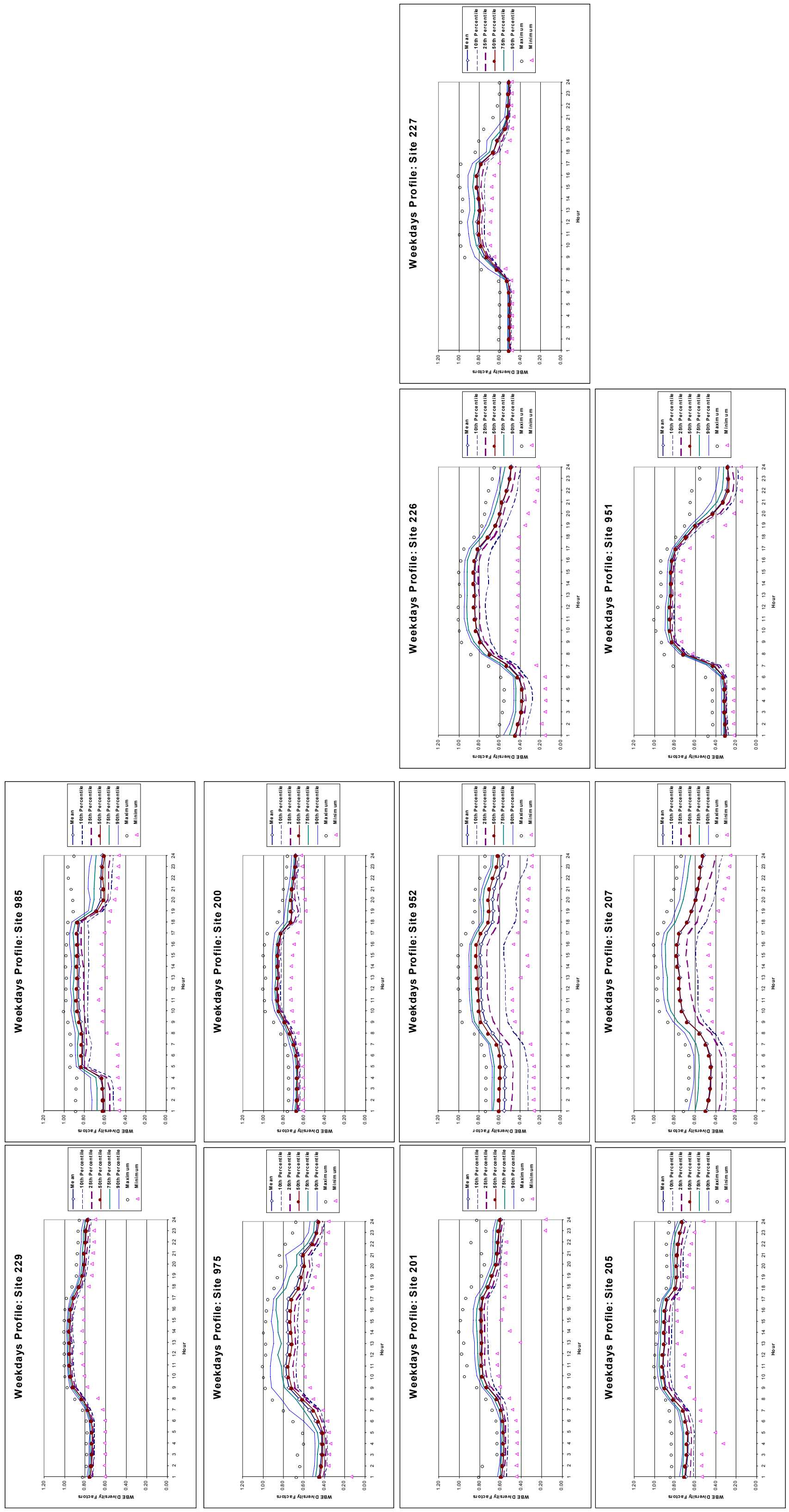


Figure 3: 24-hour, Weekday, Whole-building Electricity Profiles used for EUI Calculations (cont).

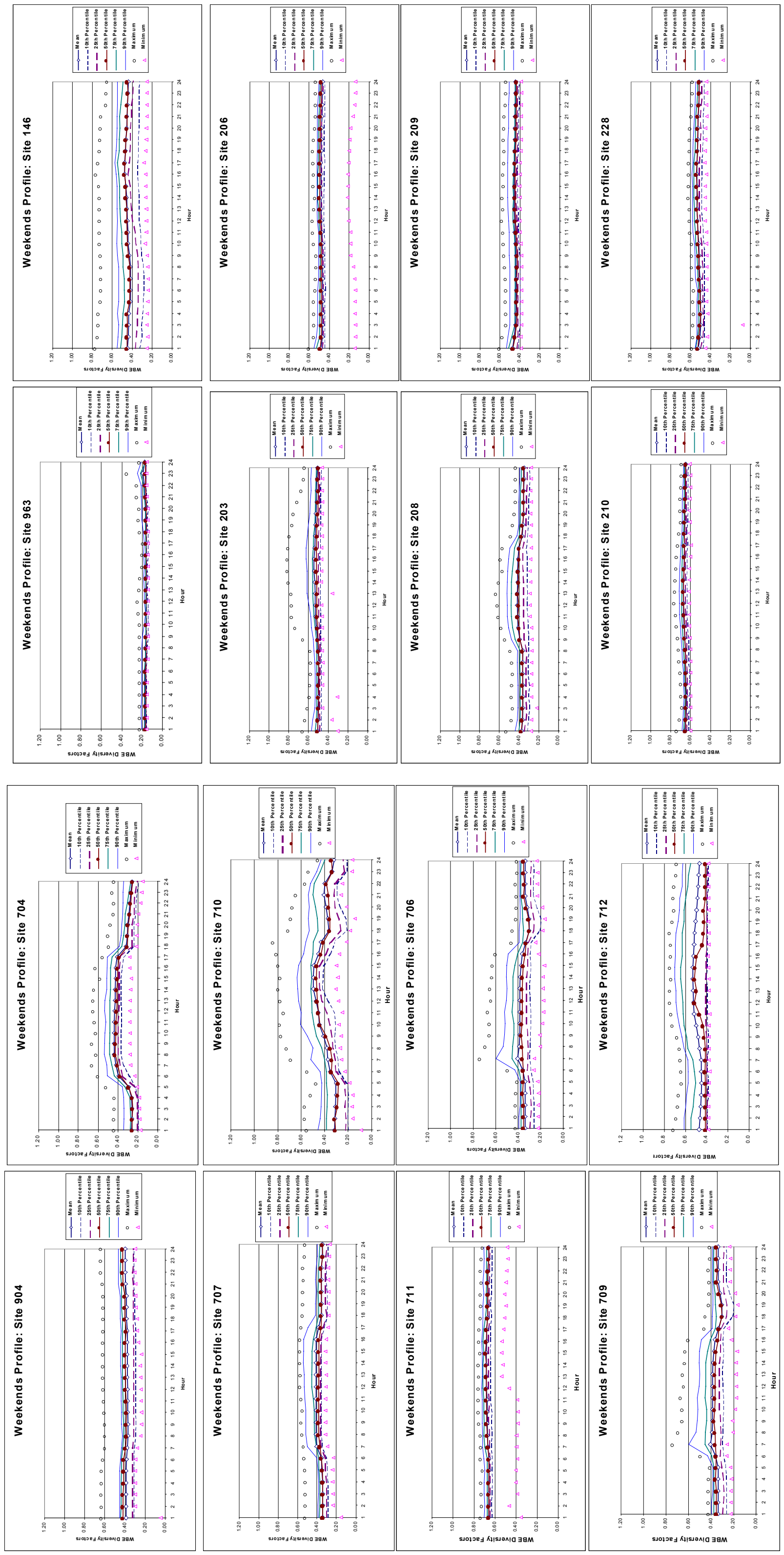


Figure 4: 24-hour, Weekend, Whole-building Electricity Profiles used for EUI Calculations.

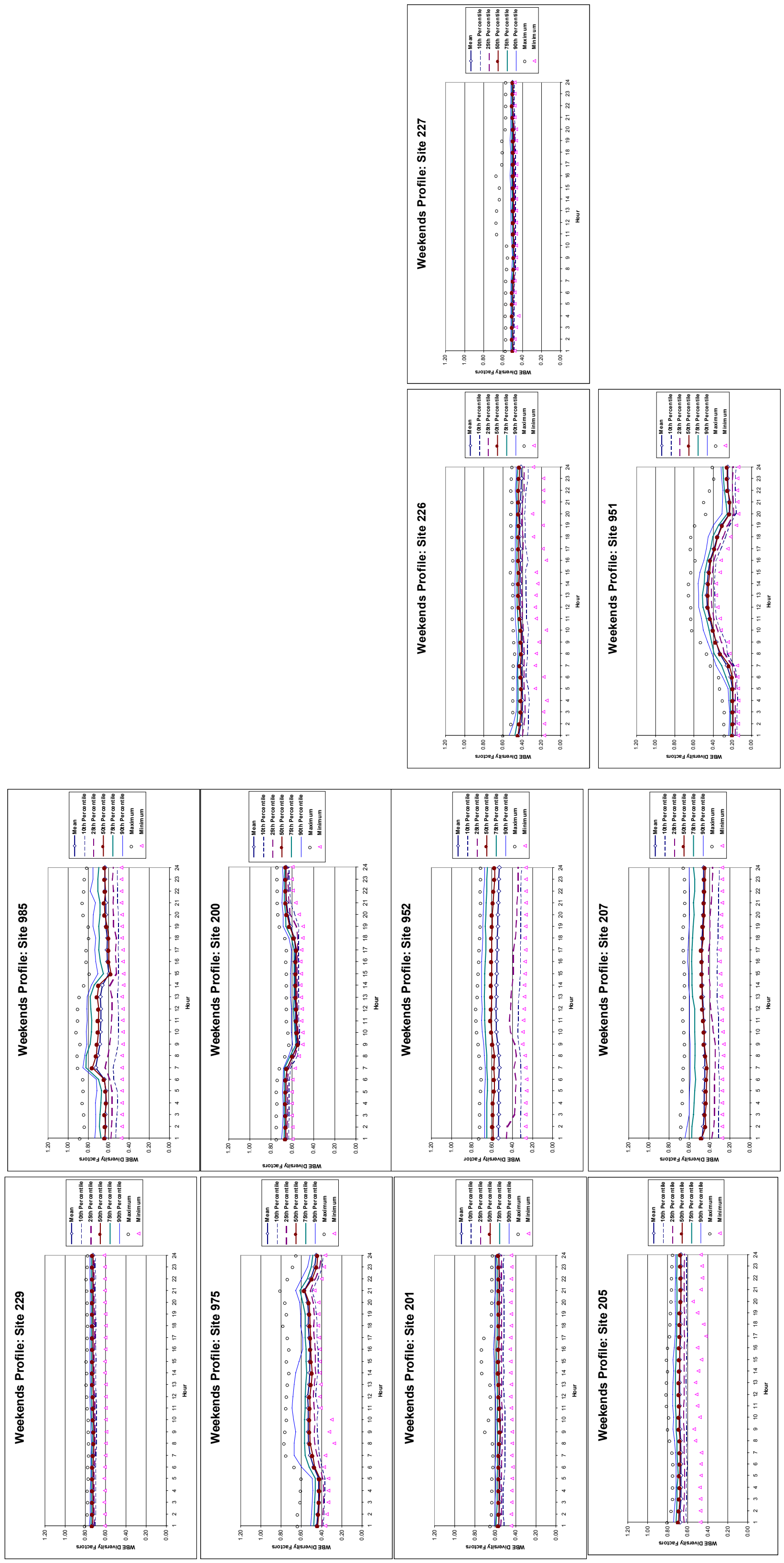


Figure 4: 24-hour, Weekend, Whole-building Electricity Profiles used for EUI Calculations (cont.).

In column 5 the building name is given, followed by column 6, which lists the city and state where the building is located. In column 7 the total conditioned area of the building is shown in square feet (ft^2). In column 8 and 9 the beginning and ending dates of the dataset presented in this report is shown.

In Table 2, column 10 and 11 the daytype data type and WBE data type are shown. The daytype data type refers to the data that was used to construct the 24-hour profiles for each building. The whole-building electric (WBE) refers to the data type that was used to construct the kWh/ft2-yr EUI that follows in Column 12, where WBE refers to the actual electricity recorded at the building utility service entrance, WBE-MCC represents data that have the submetered electricity use subtracted from the whole-building electricity use, WBE-MCC-AHU represents data that have both MCC (i.e., the building motor control centers that contain chillers within the MCC), and AHU (i.e., the electricity use of the air handling units not contained in the MCC), WBE-MCC-CHILL represents data that have both MCC and chiller electricity use subtracted from the whole-building electricity use (i.e., in buildings where the chiller electricity use is not contained in the MCC electricity use).

In Table 2, column 11 a code word is given for the type of electricity use that was used to calculate the whole-building electricity use, including: WI = Weather Independent, no heating or cooling, WDH = Weather Dependent, majority of heating supplied by natural gas & steam, WDH+ = Weather Dependent, majority of heating supplied by electric heating, WDC = Weather Dependent, majority of cooling supplied by chilled water, WDC+ = Weather Dependent, majority of cooling supplied by electric cooling & chillers, and WDHC = Weather Dependent, heating & cooling. In Table 2, columns 12 and 13 the Energy Usage Index (EUI) of the whole-building electricity consumption (kWh/ft^2-yr) is calculated by one of the following equations:

EUI = (weekday average kWh/ft^2-day x no. of weekdays per year) + (weekend average kWh/ft^2-day x no. of weekends per year).

The maximum electrical demand per ft^2 (W/ft^2) is calculated by the following equation:

$$W/ft^2 = (\text{Maximum kWh/h} \times 1{,}000) / \text{building area in } ft^2.$$

Where the W/ft^2 represents the maximum hourly demand in the database. This maximum electrical demand can be used to calculate the actual hourly whole-building electricity use in the 24-hour profiles by multiplying the diversity factor times the maximum electrical demand times the square footage for the building.

In column 14 the EUI of the whole-building electricity consumption from the motor control center (MCC) is calculated by the following equation:

EUI = (weekday average kWh/ft^2-day x no. of weekdays per year) + (weekend average kWh/ft^2-day x no. of weekends per year).

In column 15 the whole-building electricity use minus the motor control center (WBE-MCC) EUI is given, which represents the WBE after the MCC electricity use has been subtracted.

EUI = (weekday average kWh/ft^2-day x no. of weekdays per year) + (weekend average kWh/ft^2-day x no. of weekends per year).

In Table 2, column 16, the whole-building cooling (**WBCOOL)** EUI is given next. These data represent the actual chilled water production of the chiller as measured at the building boundary with a thermal meter. The whole-building cooling energy consumption ($kBtu/ft^2$-yr.) is calculated using one of the following models to correct for missing data as follows:

$$2P\ model;\ EUI = \sum_{i=1}^{365} [(Y_{int,wd} + Slope_{wd} * T_i)_{weekdays} + (Y_{int,we} + Slope_{we} * T_i)_{weekends}] / Bldg.area$$

$$3P\ model;\ EUI = \sum_{i=1}^{365} [(if\ T_i > X_{cp,wd},\ then\ Y_{cp,wd} + RS_{wd} * T_i;\ if\ T_i \le X_{cp,wd},\ then\ Y_{cp,wd})_{weekdays} + (if\ T_i > X_{cp,we},\ then\ Y_{cp,we} + RS_{we} * T_i;\ if\ T_i \le X_{cp,we},\ then\ Y_{cp,we})_{weekends}] / Bldg.\ area$$

$$4P\ model;\ EUI = \sum_{i=1}^{365} [(if\ T_i > X_{cp,wd},\ then\ Y_{cp,wd} + RS_{wd} * T_i;\ if\ T_i \le X_{cp,wd},\ then\ Y_{cp,wd} - LS_{wd} * T_i)_{weekdays} + (if\ T_i > X_{cp,we},\ then\ Y_{cp,we} + RS_{we} * T_i;\ if\ T_i \le X_{cp,we},\ then\ Y_{cp,we} - LS_{we} * T_i)_{weekends}] / Bldg.\ area$$

In Table 3, column 14, this value is converted using the following formula that accounts for an assumed chiller efficiency of 1 kW/ton, which then represents the cooling load at the utility meter:

WBCOOL kWh/ft^2*-yr. = [(kBtu/*ft^2*-yr.) / 12,000 Btu per ton] x 1 kW per ton*

In Table 2, column 17, the EUI for the whole-building heating consumption is given next (**WBHEAT).** Where the EUI of the whole-building heating energy consumption (kBtu/ft^2-yr.) is calculated as follows:

$$2P\ model;\ EUI = \sum_{i=1}^{365} [(Y_{int,wd} - Slope_{wd}*T_i)_{weekdays} + (Y_{int,we} - Slope_{we}*T_i)_{weekends}] / Bldg.area$$

$$3P\ model;\ EUI = \sum_{i=1}^{365} [(if\ T_i > X_{cp,\ wd},\ then\ Y_{cp,\ wd};\ if\ T_i \leq X_{cp,\ wd},\ then\ Y_{cp,\ wd} - LS_{wd} *T_i)_{weekdays} + (if\ T_i > X_{cp,\ we},\ then\ Y_{cp,\ we};\ if\ T_i \leq X_{cp,\ we},\ then\ Y_{cp,we} - LS_{we} *T_i)_{weekends}] / Bldg.\ area$$

$$4P\ model;\ EUI = \sum_{i=1}^{365} [(if\ T_i > X_{cp,wd},\ then\ Y_{cp,wd} + RS_{wd} *T_i;\ if\ T_i \leq X_{cp,\ wd},\ then\ Y_{cp,wd} - LS_{wd} *T_i)_{weekdays} + (if\ T_i > X_{cp,we},\ then\ Y_{cp,we} + RS_{we} *T_i;\ if\ T_i \leq X_{cp,\ we},\ then\ Y_{cp,we} - LS_{we} *T_i)_{weekends}] / Bldg.\ area$$

In Table 3, column 15, this is converted using the following formula that assumes a heating efficiency of 100%, which then represents the cooling load at the utility meter:

WBHEAT kWh/ft^2*-yr. = (kBtu/*ft^2*-yr.) / 3,412 Btu per kWh.*

Finally, in Table 3, column 16 gives the total building energy consumption in kWh/ft^2-yr for those buildings that contained all the pertinent information:

TOTAL = WBE + WBCOOL + WBHEAT

Comparison of Electricity, Cooling and Heating EUIs

The 27 office buildings represented in this study represent a range of buildings that vary from the 1.2 million square foot USDOE headquarters building in Washington, D.C. to the 42,385 square foot administration building in Dallas, Texas. Eight of these buildings, or 29.6%, are classified as "M" or medium sized buildings (i.e., less than 100,000 ft^2 and greater than 10,000 ft^2), with the remaining nineteen buildings, or 70.4%, being classified at "L" or large sized buildings (greater than 100,000 ft^2). Figure 5 shows the conditioned area of the 27 buildings contained in this study.

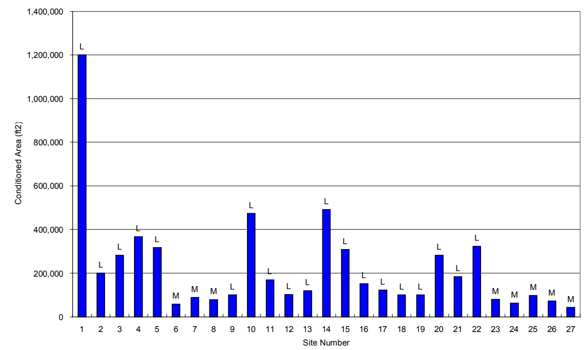


***Figure 5:** Comparison of Conditioned Area for the Office Buildings.*

In Figure 6 the whole-building electricity EUIs are shown for all 27 office buildings, as kWh/ft2-yr (lower plot), and maximum W/ft2 (upper plot). In the upper portion of Figure 6 the W/ft2 EUI for the maximum whole-building electricity use is shown. These range from a low of 1.75 W/ft2 (Tom C. Clark office building in Austin, Texas), to a high 13.04 W/ft2 (Atrium building in Dallas, Texas). With the exception of building #18 (an Atrium building in Dallas, Texas), all the buildings exhibited maximum whole-building electricity EUIs below 8 W/ft2. Eleven (50%) of the buildings had a maximum whole-building electricity use between 4 and 6 W/ft2. Ten buildings had maximum whole-building electricity use between 2 and 4 W/ft2. Two buildings showed maximum whole-building electricity use below 2 W/ft2 and three buildings (including #18) showed maximum whole-building electricity use above 8 Wft2.

In the lower portion of Figure 6 the annual whole-building electricity kWh/ft2-yr EUI is shown. These range from a low of 12.31 kWh/ft2-yr (Tom C. Clark building in Austin, Texas) to a high of 83.76 kWh/ft2-yr (Atrium building in Dallas, Texas). Of the 27 buildings 19% had an annual electricity use above 30 kWh/ft2-yr (i.e., buildings 15, 18, 21, 23, and 27), 30% had a whole-building electricity EUI of 20 to 30 kWh/ft2-yr (i.e., buildings 5, 8, 10, 11, 12, 19, 20 and 25), 41% had an EUI of 10 to 20 kWh/ft2-yr (buildings 2,4,6,7,13,14,16,17,22,24 and 26), and one building had a whole-building electricity EUI below 10 kWh/ft2-yr (building 9).

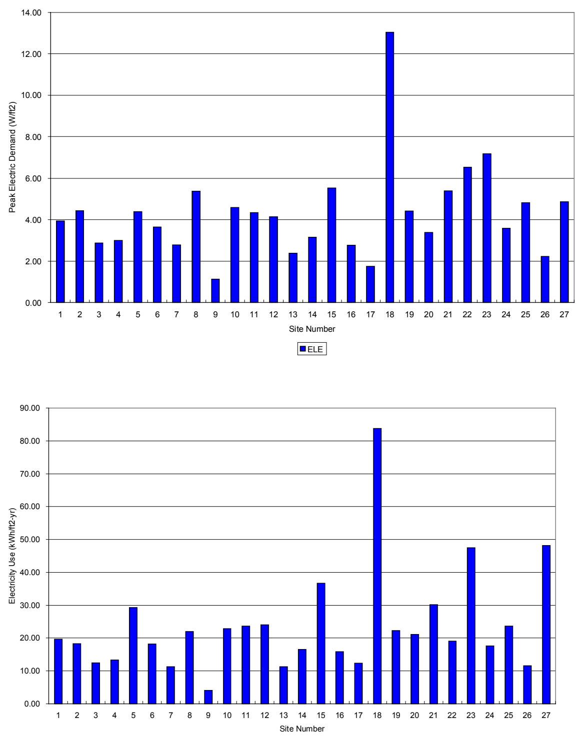


Figure 6: *Comparison of Whole-building Electricity EUIs for the Office Buildings.*

In Figure 7 the EUI for buildings that had motor control center (MCC) submetering is shown for eight buildings (i.e., buildings 10, 11, 12, 13, 15, 18, 19, and 24. Building 14 is shown but is believed to only represent a portion of the MCC use for the whole building). The MCC EUIs ranged from a low of 2.41 kWh/ft2-yr to a high of 6.89 kWh/ft2-yr (excluding building 14). In these buildings all but one (i.e., building 18) showed MCC use in the 2 to 5 kWh/ft2-yr range. In Figure 8 the MCC EUI is subtracted from the WBE EUI for the eight sites in Figure 7 and shown beside the WBE EUI for comparison purposes. Clearly, in all sites the MCC use that was submetered represented only a fraction of the whole-building, weather-independent energy use, which means that a major portion of the electricity use in these buildings is being consumed by something other than the Motor Control Centers and the chillers (i.e., lights and receptacles).

In Figure 9 the heating energy EUIs for (21) sites are shown as kBtu/ft^2-yr (upper figure) and as kWh/ft^2-yr (lower figure). These ranged from a low of 18.10 to 77.32 kBtu/ft^2-yr (5.35 to 22.66 kWh/ft2-yr). Fifteen of the 27 sites, or 55% had a heating EUI greater that 30 kBth/ft2-yr (i.e. sites 1, 6, 7, 8, 9, 10, 12, 13, 14, 20, 23 and 24). Six sites, or 22% had heating EUIs less than 30 kBtu/ft2-yr (i.e., sites 2, 3, 4, 5, 17, and 20). Six sites did not have hourly heating data available in the ESL database. Interestingly, four of the five sites that had the most consumptive heating are northern sites (i.e., Minnesota sites 6, 7 and 8, and Montana, site 9), one of the sites is a Texas building (i.e., the government center in Dallas).

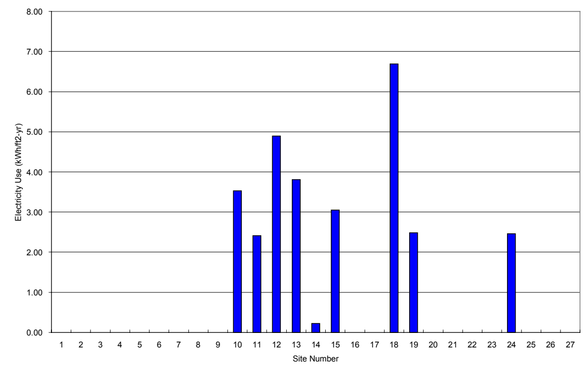


Figure 7: *Comparison of MCC Electricity EUIs for the Office Buildings.*

In Figure 10 the cooling energy EUIs for 24 sites are shown as kBtu/ft^2-yr (upper figure) and as kWh/ft^2-yr (lower figure). These ranged from a low of 5.0 to a high of 219.1 kBtu/ft^2-yr (0.42 to 18.26 kWh/ft2-yr). With the exception of a few sites (i.e., sites 18, 19, 22, 23 and 24) all of the Texas sites showed significant cooling energy use at 50 kBtu/ft2-yr and above (i.e., sites 10, 11, 12, 13, 14, 15, 16, 17, 20, 21, 25, 26 and 27). Conversely, all the Minnesota sites showed significantly lower cooling energy use (i.e., sites 2, 3, 4, 5, 7 and 8). Two of the Minnesota sites did not have hourly cooling energy data (i.e., sites 1 and 9).

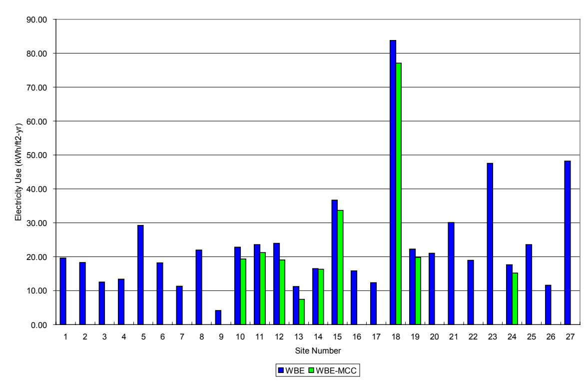


Figure 8: *Comparison of WBE-MCC Electricity EUIs for the Office Buildings.*

In Figure 11 the total EUIs are shown for 18 of the 27 sites that contained electricity, cooling and heating data. In Figure 11 the electricity, cooling and heating

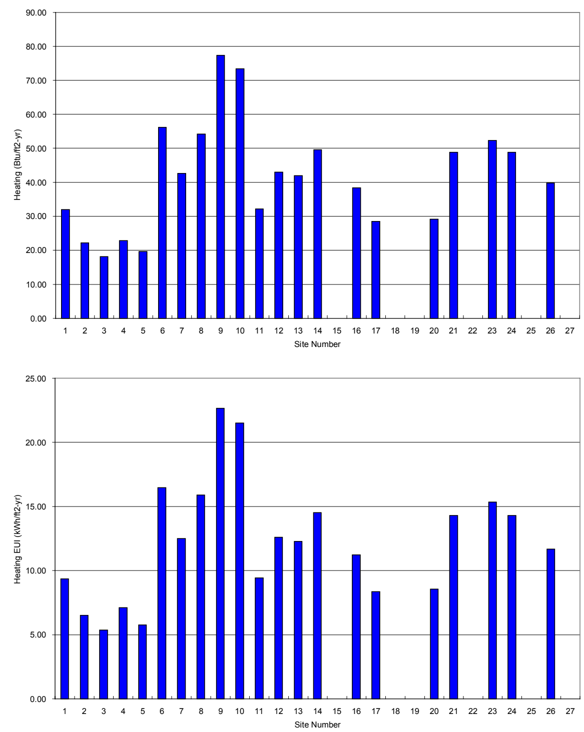


Figure 9: *Comparison of Heating EUIs for the Office Buildings.*

EUIs are shown as kBtu/ft2-hr in the upper portion of Figure 11, and as kWh/ft2-hr in the lower portion of the figure. In Figure 11 the kBtu/ft2-yr values were calculated from the kWh/ft2-yr values listed in Table 3, which include the 1 kW/ton conversion efficiency of the chillers and the 100% boiler efficiency[1]. Therefore, the kBtu/ft2-yr values in the upper portion of Figure 11 are appropriate for comparing with similar values listed by the USDOE (CBECS 1996), and others.

In Figure 11 only 5 of the 18 sites had a total EUI of 100,000 Btu/ft2-yr (apx. 30 kWh/ft2-yr) or less. Four of these sites were in Minnesota (i.e., sites 2, 3, 4 and 7). One site was in Texas (site 13). Four of the sites had a total EUI above 150,000 kBth/ft2-yr (Texas sites 10, 12, 21 and 23). In general the high EUIs would seem to indicate that there is significant potential for energy reductions. Only two of the sites (i.e., Minnesota sites 3 and 4) had a total EUI consumption at or below 75,000 Btu/ft2-yr (21 kWh/ft2-yr), which would be considered efficient. This would seem to indicate that there is still significant potential for savings in the buildings that had high EUIs.

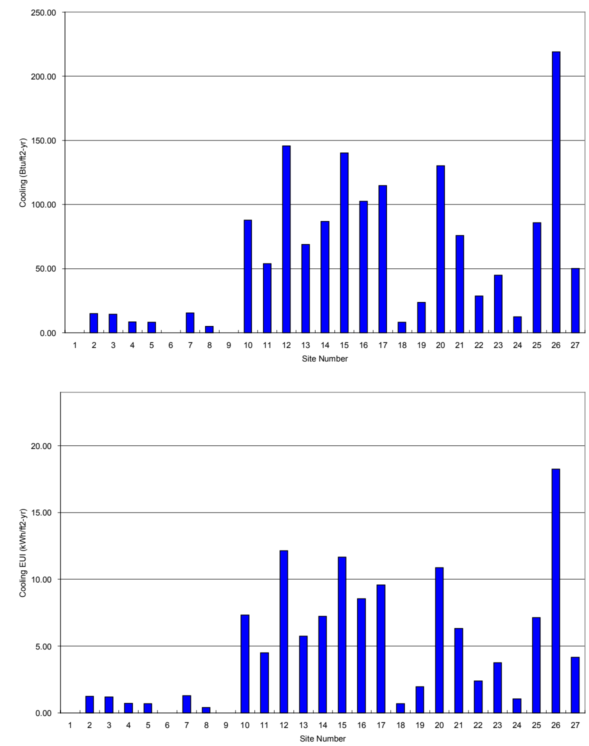


Figure 10: *Comparison of Cooling EUIs for the Office Buildings.*

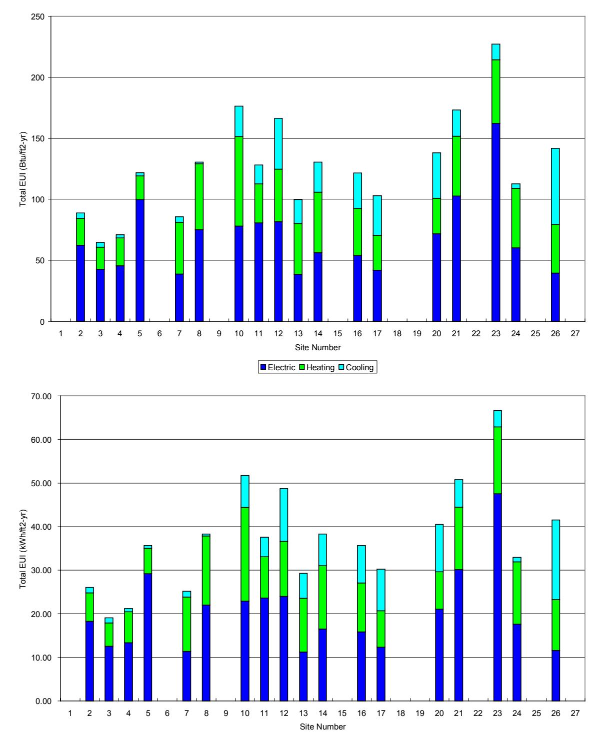


Figure 11: *Comparison of Electricity, Heating and Cooling EUIs for the Office Buildings.*

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[1] Realistically, a 70 to 80% boiler efficiency should have been used for the heating conversion factor.

SUMMARY

In summary, this paper has presented whole-building indices for 27 office buildings that have been derived from measured hourly data taken at the Energy Systems Laboratory over the course of the past 10 years. These buildings represent locations in Minnesota, Washington, D., C., and Texas. Weather-independent 24-hour, weekday-weekend daytype profiles were developed for all 27 buildings. In 18 of these buildings hourly data for heating, cooling and electricity use was available that allowed for comparative EUIs to be developed for heating, cooling and electricity end-uses.

In general, as expected, buildings in Minnesota tended to be less consumptive than buildings in Texas, due mostly to differences in cooling loads. In all the buildings, weather-independent electricity use (i.e., whole-building electricity use not associated with heating or cooling) represented the largest end-use, followed in most buildings by heating and then cooling. Very few of the buildings has a total EUI below 75,000 Btu/ft2-hr, which would indicate that there is significant potential for additional energy use reductions in the more consumptive buildings.

ACKNOWLEGEMENTS

This work relied upon data that was collected for several efforts, including the Texas LoanSTAR program, a metering program for the USDOE, a program for the State of Minnesota, and a metering program for New Horizons Technologies in Butte, Montana. The daytyping procedures used to develop the 24-hour profiles utilized the analysis developed for ASHRAE Research Project 1093. The analysis reported in this paper is part of a study performed for the Federal Reserve Bank to ascertain how measured hourly heating, cooling and weather-independent energy use varied across the United States for commercial office buildings.

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